Comparison between Phase and Polarization Sensing using Coherent Transceivers over Deployed Metro Fibers

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Lorenzo Andrenacci,[1,*] Dario Pilori,[1] Saverio Pellegrini,[1] Leonardo Minelli,[1] Gabriella Bosco,[1] Claudio Crognale,[2] Stefano Piciaccia[2] and Roberto Gaudino[1]

[1] *DET, Politecnico di Torino, C.so Duca degli Abruzzi 24, Torino, Italy*
[2] *Cisco Photonics Italy S.r.l., Via Santa Maria Molgora 48/C, Vimercate, Italy*

[*] *lorenzo.andrenacci@polito.it*

Abstract: We experimentally compare SOP and phase extraction under identical system conditions over a deployed 32-km unamplified metro fiber link for vibrations sensing applications using coherent receivers.

1. Introduction

Existing fiber networks are an important resource which can be exploited to detect anomalous vibrations affecting the cables, such as earthquakes, construction works or fiber tampering [1]. The sensing techniques proposed so far in deployed fiber networks can be divided into two main families. The first group exploits a dedicated sensing signal, either in a WDM channel or over a dedicated dark fiber [1,2], typically using back-reflected signals, ad-hoc hardware and advanced signal processing: these techniques can give spatial resolution and excellent performance in terms of accuracy, but they come at the cost of dedicated optical resources and, usually, very expensive hardware. The second family, which encompasses recently proposed techniques, is based instead on information that can be directly extracted from coherent receivers carrying live PM-QAM traffic. Among these, a significant effort has been dedicated on sensing through monitoring of the State of Polarization (SOP), which can be extracted from the coefficients of the adaptive equalizer [4]. While these solutions generally do not provide spatial resolution (or a very limited one, see [5]) but only length-integrated sensing capabilities, they result to be significantly cost-effective, since they require only marginal upgrade to coherent receiver DSP. Besides SOP, optical phase of the received signal was also proposed as a sensing metric. Recent literature claimed that it can lead to a better sensing performance [1,2], though at the expense of required special ultra narrow linewidth lasers. For instance, in [3], the authors combined a low-linewidth fiber laser with a standard coherent PM-QPSK transmission, demonstrating a superior sensing performance when using phase extraction compared to the SOP over a deployed fiber in a suburban environment and with a strong mechanical stress. In this paper, we propose a renewed comparison of the phase- and SOP-based sensing capabilities, using a different fiber installation from [3]. In particular, we consider a deployed 32-km metropolitan fiber network running underground in the Turin (Italy) downtown area, where small and controlled vibrations are induced using a mechanical fiber shaker. In such scenario, experimental results suggest superior SOP performance compared to phase in terms of background noise robustness.

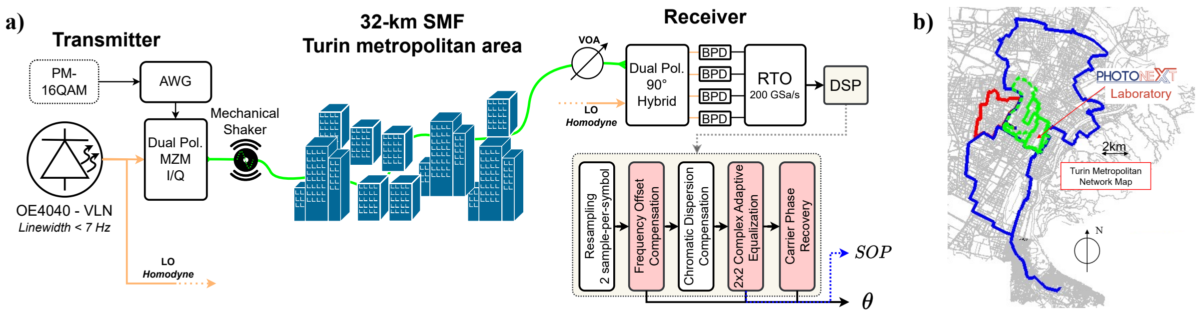

Fig. 1: a) Experimental setup. AWG: arbitrary waveform generator, MZM: Mach-Zehnder modulator, LO: local oscillator, SMF: single-mode fiber, BPD: balanced photodetector, RTO: real-time oscilloscope, DSP: digital signal processing, VOA: variable optical attenuator. b) Map of the used Turin metropolitan fiber network.

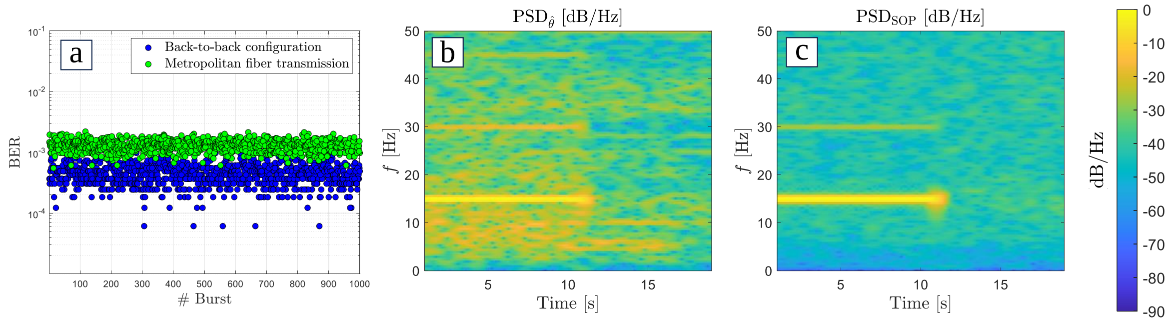

Fig. 2: a) Measured BER for the first 1000 data bursts in back-to-back and after metropolitan transmission. PSD in back-to-back configuration for the b) optical phase and c) SOP with a 15-Hz shaking.

2. Experimental Setup and Results

The experimental setup is outlined in Fig. 1a. At the transmitter side, an ultra-low noise OE4040-VLN laser, centered at 1545.17 nm and with a spectral linewidth < 7 Hz, modulates a 32-GBaud PM-16QAM signal having square-root raised-cosine spectral shape with roll-off 0.2. The experiments have been carried out on a 32-km fiber link deployed underground in the Turin metropolitan area (see Fig. 1b). As a reference, we also report the results achieved using a back-to-back configuration. Since no EDFAs were present in the metropolitan link, both BER and SOP/phase accuracy are solely determined by the coherent receiver internal noise, as in a typical unamplified link. At the receiver, we performed offline post-processing of real-time oscilloscope (RTO, at 200 GSa/s) signal acquisitions by using a typical DSP chain for standard coherent receivers. In particular, the RTO acquires signal bursts of 200 ns every 1 ms: this allows to extend the acquisition time to the range of tens of seconds, making it comparable to the typical time constants of mechanical vibrations. Each burst undergoes DSP front-end corrections, 2-sample-per-symbol resampling, frequency offset compensation (FOC), chromatic dispersion compensation (CDC), data-aided adaptive equalization and carrier phase recovery (CPR). Equalization is performed using a least mean square (LMS)-based 2×2 complex-valued equalizer with 16 taps. Note that the DSP elements manage to converge within the burst duration, yielding a mean signal-to-noise ratio (SNR) higher than 17 dB for both configurations. The corresponding measured BER over 1000 data bursts is reported in Fig. 2a.

With the presented post-processing procedure, it is then possible to retrieve SOP and phase information from each processed burst at a sample rate of $f_s = 1000$ sample/s. The signal optical phase is computed according to the algorithm proposed in [3]:

$$\hat{\theta}[n] = -2\pi\Delta\Omega n + \arg\left\{\sum_{ij} \bar{w}_{ij}^{(n)} e^{-j\Delta\psi_i[n]}\right\}, \quad i,j = 1,2 \tag{1}$$

where n is the burst index, $\Delta\Omega$ is the digital frequency offset from FOC, $\bar{w}_{ij}^{(n)}$ is the mean value of the $\mathbf{w}_{ij}^{(n)}$ element in the equalization matrix $\mathbf{W}^{(n)}$ and $\Delta\psi_i[n]$ is the i-th element of the phase rotation vector $\Delta\Psi[n]$ from CPR. SOP is instead extracted from the DC components of either column of $\mathbf{W}^{(n)}$.

To assess the achievable sensing capabilities of these quantities, we induced controlled vibrations on the metropolitan fiber link, by means of a mechanical shaker placed right after the transmitter (see Fig.1a). A low-frequency (i.e., few Hz) signal generator drives the shaker to induce a sinusoidal stress at tunable frequency over the fiber.

The effect of the vibrations induced on the fiber are studied by means of spectrograms, computed for both optical phase and SOP using the same procedure. At first, the DC component of the signals is removed with a high-pass filter, implemented subtracting from the original signal a moving-averaged version of it, with a sliding window of $T_{\mathrm{win}} = 100$ ms. Subsequently, the power spectral density (PSD) is computed and smoothed through a moving average operation with a window $T_{\mathrm{win}} = 100$ ms. Spectra are normalized to enhance the visualization of the relative power levels between the points where the vibration is present and the noise floor. In the case of SOP, the PSDs of the three individual Stokes parameters are summed up before averaging (as done in [6]).

The results obtained for an acquisition of 20 seconds in the back-to-back configuration are reported in Fig. 2(a-b). In particular, the signal generator controlling the mechanical shaker has been configured to generate a sinusoidal signal with a frequency $f_{\mathrm{vib}} = 15$ Hz during the first $\sim$10 seconds of the acquisition and then turned off. The vibration is clearly detectable in the PSDs of both the optical phase and SOP, though with different sensitivity:

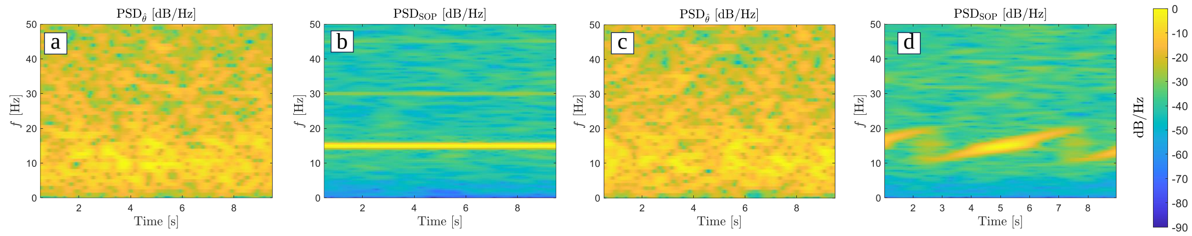

Fig. 3: Power spectral density after metropolitan transmission of a) optical phase and b) SOP for 15-Hz shaking, c) optical phase and d) SOP for a shaking frequency swept from 10 Hz up to 20 Hz every 5 seconds.

the spectral component at $f = 15\,\text{Hz}$ is indeed the strongest one over the whole time interval in which the mechanical shaker is on. However, it is around 20 dB above the noise floor for the optical phase, whereas it achieves a separation of around 40 dB for the SOP. Hence, the optical phase appears to be more sensitive to external perturbations, i.e., characterized by a noisier PSD, also considering the fact that in a back-to-back configuration no strong disturbances are present. These considerations are confirmed by the results obtained in the 32-km metropolitan fiber configuration for an acquisition of 10 seconds, as reported in Fig. 3(a-b). In this case, the mechanical shaker was active for the whole duration of the acquisition. At the output of the metro fiber, no information on the induced mechanical vibration can be retrieved from the PSD of the optical phase. In this scenario, the spectral component relative to the induced vibration is completely immersed in a "background" noise, likely generated by the micro-vibrations caused by the metropolitan environment on the deployed fiber. These micro-vibrations might indeed originate from a broad range of urban activities, such as car traffic, construction works, etc. On the contrary, the SOP proves to be more robust to external perturbations, since the vibration is once again the dominant spectral component with a separation around 30 dB from the "background" noise floor. The same applies for a shaking driven by a chirped sinusoidal signal whose frequency varies from 10 up to 20 Hz with a periodicity of 5 seconds, as shown in Fig. 3(c-d).

While these results might seem contradictory to those outlined in [3], it is important to point out the different scenarios in which they were obtained. In particular, two aspects need to be highlighted, namely the transmission environment and the type of excitation applied to the optical fiber. In this work, data transmission was conducted across a metropolitan optical fiber network situated in the downtown area of Turin, which represents a noisier environment with respect to a suburban area. Moreover, the excitation induced by means of a mechanical shaker driven by a sinusoidal signal is intentionally quite weak in amplitude, in order to test the ultimate sensing capabilities in the two cases. Therefore, this work extends the discussion over the comparison between phase and SOP sensing under different propagation conditions, showing that SOP seems to be more robust when subject to weaker perturbations and in noisy environments.

3. Conclusion

In this paper we have presented a comparison between sensing capabilities of coherent receivers designed to extract the received optical signal phase and SOP from the internal DSP. In the scenario of this paper, SOP appears more robust than phase to background noise compared. In addition to this environment-dependent conclusion (for instance, [3] observed instead an advantage for the phase approach), it's essential to highlight that, while SOP extraction is a relatively straightforward process, requiring only a minor modification to the receiver DSP, the use of phase information would require a total re-engineering of the coherent transceiver since, as shown in our work and in [3], it requires a very narrow-linewidth laser (i.e. with low phase noise), significantly enhancing the cost.

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